Ernie Majer Narrative

I came to the Lab in the summer of 1974. The Earth Sciences Division didn't exist, but there was a Geothermal and Geosciences Sciences Program under Paul Witherspoon and Ken Mirk that was then part of the Energy and Environment Division, which in itself had only recently been established. I was a graduate student working on my Ph.D. in geophysics under Tom McEvilly at U.C. Berkeley at the time, and I was very interested in working on geothermal projects. I had read about some interesting geothermal work in New Zealand at the time, and when I told Tom about it, he mentioned something about "this one professor in (Geological) Engineering that's doing geothermal work at the Lab"—so that's how I got to know Paul.

It turned out that Norm Goldstein, Frank Morrison, and Harold Wollenberg were leading a geothermal exploration technology project as part of Paul's program, and wanted someone with my seismological background and interests. It was pretty clear that seismological methods could provide valuable information for geothermal exploration and, moreover, that these methods also offered precise monitoring of geothermal reservoirs already under development.

Once at the Lab, I got involved in a big geothermal field study going on in northwestern Nevada at the time. This was in the Beowawe area, where numerous hot springs exist. I also did a seismological exploration of The Geysers, in Sonoma County, a former hot springs resort which we were using as a kind of laboratory—to test our exploration instruments and data processing/interpretation techniques for locating and assessing potential geothermal sources. We could then apply these methods in exploring and assessing other possible sites. For example, would a map showing the distribution of seimic events at The Geysers correspond to the geothermal reservoir area—that is, provide us with a seismic signature of a geothermal site? And if so, could similar seismic activity found elsewhere lead us to similar, as yet untapped geothermal sources?

In conjunction with our investigations at The Geysers, which we continued to study for the next 25 years, I also worked on developing the Automated Seismic Processor, or ASP, something I had started with Tom McEvilly as a graduate student, which was the first mobile, computerized processor to identify, locate, and measure very small seismic events (micro-earthquakes) in real time. The motivation for developing the ASP was the need to simplify routine micro-earthquake data acquisition and reduction, as well as improve the cost effectiveness of geothermal investigations. Processing data from a large number of micro-earthquakes, which you inevitably encounter in applying seismic techniques, turned out to be quite time consuming and expensive. So we had to figure out a way to make it easier on ourselves, make it practically and economically feasible to do advanced seismic surveys as part of geothermal exploration. The ASP was a big help in this. In the '80s, to take advantage of dramatic improvements in CPU and memory, we built an updated, faster version of the ASP, which could also save waveforms. I should mention that the ASP won an R&D 100 award in 1984.

I also did similar work with the ASP at the geothermal field in Cerro Prieto, Baja California, Mexico, about 20 miles south of Mexicali, which at the time was the only liquid-dominated geothermal system generating electric power on a commercial scale in North America. There, we monitored the microseismicity of the geothermal production area, conducting three detailed micoearthquake (MEQ) studies. The objective of this work was to characterize the seismicity within the immediate production zone, relative to known levels of "normal" seismicity for this area (it was well-known to be seismically active). In this way, we could get some idea of the impact of energy production there. I should mention that much of this seismological work related to geothermal investigations became the core of my Ph.D. dissertation, which I finished in 1978, after which I came aboard as an LBL staff member.

This period was also one of increased interest in nuclear waste disposal, and ESD was in the forefront of that, first with the work in Sweden, the Stripa mine, which had started in 1977, and then with other studies in the U.S. Specifically, in 1980, I was part of a team that conducted microseismic activity studies within the Climax Granite repository at the Nevada Test Site, evaluating techniques for monitoring the integrity of potential nuclear waste repositories. We wanted to determine the suitability of granite, or hard rock, as a repository medium. Using acoustic emission and microseismic techniques, including the ASP, we studied the relationship between rock failure and stress release relative to thermal effects, radiation degradation, and canister spacing. Placing nuclear waste in the repository increased the seismic activity in the surrounding area, and we studied the effect that activity had on the rock, whether it induced or extended fractures.

In 1982, Tom McEvilly (who became director of the division that year) and I, along with a number of others, started the Center for Computational Seismology (CCS) at the Lab. The Center filled the need for a user-based, user-friendly facility featuring systematic advances in computing technology applied to a wide range of seismological problems. Two of the most basic problems geophysicists, particularly seismologists, had were a lack of data compatibility and the lack of an integrated analysis system. Seismologists not working with conventional reflection data would have to develop or obtain elaborate software packages just to access and archive their data. CCS interacted with LLNL, USGS, and DARPA in establishing a mutually acceptable data-exchange format. This combined effort enabled the exchange of important data sets, thus making cooperative seismological efforts much easier than before. CCS got bigger and bigger in the 1980's—toward the end of the decade, CCS not only carried out basic studies in earthquake-source mechanism and reflection seismology work, but the full gamut of seismic research programs.

Around this time I did a lot of work involving advanced vertical seismic profiling (VSP), in which sensors, after being lowered into a borehole, pick up seismic signals (vibrations) artificially created by a heavy tractor-like vehicle. These seismic signals that travel through the ground come in two forms: P-waves (primary, compressional waves), which cause rocks to move in the same direction as the vibrations, and S-waves (secondary, shear), which cause rocks to move perpendicular to the vibrations. How fast these P- and S-waves travel, and the rate at which they lose their energy, tells a lot about the rocks through which they pass. At this time we used VSP in a number of important studies, including the ones at Parkfield, on the San Andreas Fault, started in the mid- and late '80s and continuing up to today.

Also in the early 1980s I also began some work involving hydraulic fracturing, both at the Avery Island salt dome in Louisiana and at Canada's Underground Research Laboratory near Winnepeg. These projects involved the use of high-pressure fluids to create fractures in the rock underground. First developed as a means of increasing the productivity of oil and gas wells in tight formations, it has since been used in connection with waste disposal, solution mining, geothermal power production, and tectonic stress measurement. We also applied seismic techniques to the mapping of hydrofractures, to study the processes by which rock fails when fractured over time by water under high pressures, and the release of seismic energy during the fracturing process. Fractures are so important in all these reservoir systems, because they are the main conduits for fluids either flowing into the system (as in geothermal and oil wells) or flowing out of the system and potentially transporting materials away from it (as in nuclear waste repositories).

During this time, we realized we could apply advanced tomography—the process of transmitting vibrations through the ground for recording by a sensor, and then transforming the resulting data into a geological map—to characterize and monitor heterogeneous rock (the combination of rock matrix, fractures, and fluidswithin the rock). This would have a wide variety of uses. In the late '80s we used such techniques at the Grimsel Rock Laboratory in Switzerland. The work there, part of a DOE/NAGRA joint research program (NAGRA is the Swiss organization addressing the storage and disposal of nuclear waste generated in Switzerland) involved extensive geophysical imaging with seismic techniques, demonstrating how geophysics could reveal hydrologically significant features, such as fractures. Seismic-wave propagation in fractured rock had become a key mapping method for defining fracture characteristics (such as density, orientation, and spacing). One of the principal goals here was to investigate how fractures could be located, using controlled *P*-, *SV*-, and *SH*-waves to image the site. We also conducted seismic imaging in a Central Valley (California) petroleum reservoir, using VSP, crosshole seismic, pressure monitors, and tiltmeters to determine the principal stress directions and the path of hydrofracturing.

Nuclear waste repository studies got more intense and complicated after Yucca Mountain (Nevada) was chosen as the site of focus for a national nuclear waste repository in 1983. We were involved in developing the site-scale flow model in the '80s, but we hadn't done any geophysical work there. Yucca Mountain had its own special set of problems for seismological study; its geologic structure and volcanic rock cause many geophysical anomalies, and the faulting there additionally complicates the geophysical signature of the site. In the early and mid-1990s, ESD started to get heavily involved in Yucca Mountain characterization and modeling. In the summer of 1993, Tom Daley, Mark Feigner, and I conducted a surface seismic reflection profiling and VSP survey of the site. We hoped through this work to evaluate the use of high-resolution geophysics for detecting and mapping faults, and fractures, and to image the heterogeneities that are important to fluid flow there. This was also the first attempt at using advanced seismic imaging techniques to determine the geologic features within the Yucca Mountain tuff. Our studies found that Yucca Mountain was composed of a complex overlapping structure of tuffs that vary in physical properties throughout the proposed repository site, to a much greater degree than people had thought previously.

All during that time, but most prominently in the late '80s, ESD started getting into environmental remediation in a big way, mostly with our work at the Kesterson Reservoir Selenium Remediation project in Merced County (California). As before, we felt that geophysical and seismological imaging tools could be put to good use in this effort. Using such imaging, we could examine the relationship between seismic and hydrologic properties that control contaminant transport near the surface of polluted areas, as well as mapping the porosity, structure, and soil composition, and thus determining the permeability of the subsurface. The results of studies there had led to two cost-effective remedial measures: in 1986, drainage-water deliveries into the reservoir (containing 300 ug/L of selenium per year) were stopped, and in 1988, when one million cubic yards of "clean" soil were imported to fill the low-lying areas of the former Kesterson Reservoir. These actions together eliminated a contaminated aquatic habitat that had caused substantial waterfowl death in the early '80s.

But in addition to cleanup work, and the ongoing search for alternative sources of energy like geothermal, our methods could also be used to enhance the yield of oil and gas reservoirs, which of course have been the standard sources of energy in the 20th and 21st centuries. U.S. oil fields, while being exploited and pumped throughout the 20th century, still contained quite a lot of oil—but this oil isn't as easy as before (say, up to the '70s) to extract from the ground. Oil fields can stretch over hundreds of miles, and the oil within them could reside in multiple, but isolated reservoirs. We realized we could use seismic imaging and seismic profiling techniques to locate the isolated oil pockets in the big fields, which we could then access by knowing better where to set up a well network. We would thereby not only get at this resource, we could also avoid millions of dollars in dry wells if we could pick the right place to drill them. To do this, we needed to accurately describe and model the underground landscape of existing "depleted" fields.

To identify the dominant fluid paths, we need geophysical information. Geophysics has much in common, as it happens, with medical imaging. Both rely on a signal transmitted through a body. Both attempt to "image" what features in the solid body cause the signal to be transformed. But in geophysics, the bodies are not foot-wide human beings (who can be probed from every direction), but miles-wide and miles-deep expanses of earth, accessed only from boreholes about 10 inches in diameter.

In the early '90s, we focused our oil-field work on two sites in Oklahoma, Conoco's Newkirk site and the University of Oklahoma's Gypsy site. We needed to detect and map the connective pathways, made up largely of fractures, which enabled fluids to flow underground. One of our emerging methods for such activity was crosshole tomography, in which both the signal source and the receiver operate underground from inside boreholes, which produces a higher-resolution map. Where we could place seismic receivers in two or more boreholes, we could produce 3-D maps. Also, previous high-frequency sources could achieve better resolution, but frequently the ground would absorb such signals. We improved our imaging by making high-powered, high-frequency transmitting sources that generate signals not so easily absorbed by the ground.

In the 1990s and early 2000s, we did similar kinds of work in gas fields. As part of DOE's Natural Gas Program, we developed geophysical methods for mapping the fractures that control flow in naturally fractured gas reservoirs. We could by then often determine fracture trends, but we couldn't provide the resolution necessary to site well based upon fracture permeability. In the Cascade Mountains in southern Washingon, and at the ConocoPhillips San Juan Basin natural gas field in New Mexico, we used high-resolution fracture identification methods (such as logging, single-well seismic profiling, and vertical seismic profiling) in conjunction with previously acquired 3-D surface P-wave imaging, to determine the best techniques for not only locating fractures, but quantifying their properties in a way that allowed us to identify the fractures that controlled fluid flow. In addition, since seismic data collected at the surface is often all that is available for mapping such sites, we also wanted to develop a methodology for extracting as much information as possible from surface data.

All in all, we were successful in deriving images indicative of fracture characteristics, with each method (surface seismic, VSP, crosswell, single well) contributing a different image of the site, produced at a different scale. We also developed processing techniques that enabled us to integrate the various maps, so that the imaging done by one technique could be readily "informed" by imaging from another, using innovative data processing techniques that we developed.

Also in the early '90s, I personally assumed higher positions of leadership. I was head of a number of projects reaching back into the 1980s, but in the mid-1990s, I became head of what was then called the Subsurface Geosciences Department, but which soon morphed into the Geophysics and Geomechanics Department. This department focused on subsurface process analysis, monitoring, and imaging, and included the two facilities, the aforementioned Center for Computation Seismology and the newer Geosciences Measurement Center, which provided a base of expertise to support field and laboratory work on fluid flow and transport, microbial behavior, and geophysical imaging. Not long after that, in 2000, I became head of the Fundamental and Exploratory Research Program, which was basically the staging area for basic science that was applied in all the other ESD programs, especially in Energy Resources and Environmental Remediation Technology. And of course, since Bo's untimely death last November, I've been Acting Director of ESD.

What with the recent developments affecting ESD, specifically the $500 million Helios Project, and its creation of the Energy Biosciences Institute (EBI) here at Berkeley Lab, it's an extremely exciting and important time to be a part of ESD. EBI intersects with much of what we've already started and what we want to continue to do here within ESD. It will be dedicated to long-term research into the production of alternative fuels, converting fossil fuels to energy with less impact on the environment, maximizing oil extraction from existing wells in environmentally sensitive ways, and finding ways to store or sequester carbon so that it does not get released into the atmosphere. I feel, and certainly [Berkeley Lab Director] Stephen Chu feels, that we're at the center of all of this.